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Signal Investigation for Low Frequency Active (LFA) Sonar

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EXECUTIVE SUMMARY

The resurgence of interest in active sonar brought on by the quieting programs of various naval propulsion systems and the expanding naval interest in operations in littoral regions, has resulted in renewed interest in advanced waveform designs for these sonars. A second motivation for the use of coded signals is their ability to permit wideband multi-user operations among co-operating units and to run the sonar in both mono-static and bi-static modes simultaneously. As more experience has been garnered with low-frequency active (LFA) systems and their deployment in multi-static operations, it has become clear that the use of a single pulse type which can yield good simultaneous resolution in both target Doppler and range is required. In the past a Doppler sensitive (DS) waveform, such as a long continuous wave (CW) signal was used to resolve target speed and a wide bandwidth frequency modulated signal, linear FM (LFM) or hyperbolic FM (HFM) was then used to resolve the range. These modulated FMs are considered to be generally Doppler insensitive (DI) signals. In the littoral regions, the separation of low Doppler targets from clutter or bottom reverberation argues for the use of a composite signal which can in one pulse have the Doppler resolution of the DS signal while at the same time provide the range resolution of the DI signal.

Further evidence of the need for such a waveform has been gained from Naval exercises where it has been noted that the trackers do not perform as well with alternating signals as with a composite pulse, since the alternating pulse mode results in higher false alarm rates and/or missed target detections. In multi-static scenarios it has been observed that some receivers will see more target Doppler than others, depending on the target radial velocity with respect to the transmitter/receiver geometry and once again detection, tracking and classification opportunities are missed when multiple signals are required to resolve Doppler and range separately.

One further complication with the selection of signals for use in LFA sonars results from the varied transmitter and receiver systems that are available. In some operations the source can be an active sonobuoy with limited output power level and battery life. Here the selection of a composite waveform with both DS and DI properties will enable the sonar system to detect simultaneously both low and high Doppler opportunities resulting in more target detections with less energy than is possible with conventional waveforms. In the case of a horizontal line array transmitter, coded waveforms can be used to better produce the range, Doppler, angular, underwater acoustic image. With the omni-directional transmitter the use of coded signals can further enhance the detection and tracking of both the close-in and longer-range targets with their significantly differing noise backgrounds using just one transmission.

In this report we attempt to identify as many of the pulse types and individual designs as we were able to locate and then give an overview of their relative advantages and possible applications in some operational scenarios. We then selected a couple of the more promising pulse designs, a pulse train with multiple FM sub-pulses, (the PTFM) and a Doppler sensitive probing waveform that has been optimized for a low integrated sidelobe level (ISL) which in turn means low interferences among scatterers located at

different range bins. We then discuss the possible impacts of these two signals on their respective receiver designs and list some alternatives to the matched filter currently used in today's receiver designs. Both mismatched filters and an iterative adaptive approach are identified and as the literature suggests, outperform the data-independent matched filter methods.

Based on this review and signal listings, this report concludes with a recommendation for follow-on work whereby the new probing waveform design is explored in more detail using computer simulation and if possible some sea-trials data.

TABLE OF CONTENTS

ABSTRACT
This report describes the categorization of sonar waveforms that are applicable in multi-static low frequency active (LFA) sonar systems. Two discriminators are the continuous transmission systems and the pulse type transmission systems. Within the pulse type, the waveforms are further classified as to their Doppler and range resolving capabilities. Some signals are referred to as Doppler sensitive and have good Doppler resolving capabilities and low to medium range resolution, while others are referred to as Doppler insensitive waveforms and possess good range resolving capability but moderate to low Doppler resolving properties. Much of this recent work in waveform design has concentrated on signals with both good Doppler and range resolving abilities and are referred to as composite signals.

A catalogue type description of signals applicable in each grouping is presented for both continuous and pulse type systems along with a discussion of the impact these signals can have on the sonar receiver signal processing. In addition, some of the recent receiver algorithm work uncovered as part of this pulse review is also included. While some of the newer signals have not been fully evaluated in at-sea trials, the recommendation is made for more detailed investigations of two of the signals identified.

Signal Investigation for Low Frequency Active (LFA) Sonar

1. INTRODUCTION

With years of research and study the detection of underwater targets remains an ever challenging demand from the naval users of the sonar systems. The ray-path geometries encountered in most sonar deployments, together with the motion effects of the water, the target and the sonar platform(s) create an environment that is commonly characterized as a time-varying multi-path channel. In his aptly named paper "Medium Constraints on Sonar Design and Performance", John P. Costas[1] summarized pretty much the medium constraints on sonar design and performance. Costas then went on to design a class of detection waveforms having nearly ideal range – Doppler ambiguity properties[2] that set a level of performance for most active sonar systems. These papers set the background from which a whole host of researchers[3-7] have proposed specialized probing waveforms for use in various sonar systems and environments.

The purpose of this report is to identify the key types of pulse designs and to list many of the leading designs in each category. From this catalogue we will try to identify a few promising types which may be worthy of further investigation. Along the way we have identified some new approaches to receiver design that also may be worthy of further investigation and we briefly describe a few of these algorithms. Much of the newer work has resulted from the sonar system designs that have progressed from medium frequency mono-static, to low frequency active (LFA) mono-static, to LFA bi –static, to LFA multi-static. Here the classical pulses, the continuous wave (CW) and frequency modulated (FM) signals were enhanced by Costas designs of frequency hopped (FH) coded signals and now to the phase modulated or random phase (RP) signals, the comb signals, so called by virtue of their comb like spectra, to the newer cyclic algorithm designed sequences with their good aperiodic autocorrelation and their unimodular properties[8]. In addition, some sonar designers are promoting the use of continuous active signaling[9] as opposed to the pulse type and these designs bring another set of challenges to the sonar user.

The Canadian Navy is considering an upgrade to their current sonar capability and DRDC - Atlantic is attempting to take a lead in sorting through the many system capabilities, to help with a definition of some key attributes for a multi-static LFA sonar. While the DRDC - Atlantic mandate is quite broad, this report should assist both the Navy and the Laboratory, through the review of much of the work in signal design, to be able to select candidate signals and processing for further investigation. The system requirements can be very broad and there are now pulse or signal designs that have been specifically designed to address each of these unique applications.

A few examples are:

1. Marine Mammal mitigation; the lowering of the effect of the LFA sonar signal on the mammal population and the environment. Here designs which are much lower in amplitude but longer in duration are used and have been shown to be

equally effective at submarine detection as the higher intensity, shorter duration signals.
2. Multi-user operation where instead of dividing up the available sonar spectrum into pieces for each user, all users can now have the full sonar bandwidth available and the interference is eliminated through code division multiplexing.
3. Energy conservation and peak power limitations for transmitter amplifiers need to be considered along with the sonar bandwidth limits. Here again newer pulse designs have been found which reduce the power and bandwidth demands while maintaining the long range detection performance required for the sonar.

One quickly sees the problem when considering along with these examples others such as the sonar's role in operations and the diverse environmental backgrounds in which operations are to be carried out. To meet these wide ranging requirements, it is not hard to understand why so many signal designs have been formulated.

In the next sections of this report we shall discuss signal categories to better understand the current classification and discuss some signal types that can fall into more than one classification. We will then briefly discuss continuous active signals and their perceived advantages and then outline the various pulse type signals that have been identified. With each type we shall attempt to list some of their salient features. Following the pulse listings we will discuss the impact of two of the more promising types on the receiver signal processing. Generally the new receiver processing that some classes of signals can benefit from may also be applicable to other pulse designs as well.

We shall then conclude this note with a summary of the key findings and go on to make recommendations for some follow-on work that may be most applicable to the multi-static work at DRDC.

2. ACTIVE SONAR SIGNALS AND THEIR CATEGORIZATION

In the past the active sonar was thought to require only two signal types, the long continuous wave (CW) and the higher bandwidth linear frequency modulated (LFM) or linear period modulated (LPM) signal. The thinking at the time was that the long CW would be a good detection signal when the target was moving and the background against which the detection was to be made was mainly ambient noise. For the slower moving targets where the background is reverberation, the wider bandwidth signal with the good resolution in range and modest Doppler capability was considered as good as could be done. In deep water operations this approach could be tuned to work fairly well but as the requirement expanded to provide good detection ranges in shallow water, these two signal types were found to be very much lacking. Part of the problem is caused by the environment, with the surface ducts and shadow zones requiring the use of bottom bounce paths that may need to be exploited. Along with the power of the sonar required, the medium also sets some limitations. Here we are referring to the ray-path geometries together with the motion effects of the water, the target and the sonar platform. In order to deal with this time-varying, multi-path channel, new signal designs were required and

have been developed. With these new signals there has been the attempt to include medium parameters in the system design so that detection performance is improved through the signal's range and Doppler resolution.

This has led to signals often being referred to as Doppler sensitive (DS) or Doppler insensitive (DI) depending on their resolving properties. However some designers took the mathematical approach to pulse design and while theoretically their signals were excellent, a lot of their promised gain was not achieved in practice due to the medium effects.

In some designs the key attributes are the signal duration (T) and the signal bandwidth (B) and the resulting time-bandwidth product (TB) is a measure of signal performance. Some sonar designers then advocate continuous transmission of long coded signals be they LFMs or M-sequence signals and these have been shown, when properly processed in the receiver, to provide some gain with respect to the CW signal but against the slowly moving target a properly designed and processed FM was still very competitive. We identify two continuous wave signals further on in the signal descriptions and discuss their possible applications.

In some operational trials of LFA multi-static sonar systems there have commonly been lost or missed contacts due to the long time often used between transmissions and the fact that these exercises tended to use a DS pulse followed by a DI pulse in an alternating manner. It has been observed that depending on the geometry for the source, the target and receivers, some receivers will see only very low Doppler for the same target as others will see a higher Doppler. This causes tracks to be lost and detections not to be made, especially in the track before detect systems when the alternating pulse type approach is used. The solution to this problem that has been proposed is to use a combined DS/DI signal and the US Navy has called for proposals for the design of such signals that could be included in the active sonobuoy. We will discuss some of these composite signals and this classification does result in some signals appearing in both the DS grouping and the composite grouping depending on receiver processing or signal design parameters.

Another feature of the active sonar signals that needs to be considered in their design is the practical considerations of constant modulus and total energy. Some signals that are not unimodular will need to be normalized such that the total energy is consistent with equipment capabilities; i.e., the power amplifiers, and this can add an additional constraint on the performance expectation for these pulses. With battery powered sources, such as the active buoys, there can also be constraints on pulse length and pulse repetition rate in order to have the sources in service for a reasonable number of hours. The other practical item for consideration is pulse bandwidth. Some designers have considered an optimization approach based on the magnitude spectrum of the transmit waveform desired. They then look to the shortest possible duration for the pulse to produce this spectrum and hence maximize the ping rate or they look to the longest possible duration and hence a minimum pulse rate. The former requires higher time domain peak power and the latter has the lower peak power requirement.

One further consideration that is a factor in signal design and selection is the number of transmitters and the number of receivers in the system. In most cases we are dealing with a single omni directional transmitter, perhaps with a few elements for vertical directional gain and multiple receivers, be they the directional elements of a line array or sonobuoys or circular arrays. Such a system is referred to as a MISO or multiple input single output system. In some other cases there can be multiple outputs and multiple inputs as per a line array of transmitters. This case is referred to as a MIMO system. In this case the pulse design can add in the desired angular properties to produce the angle-range-Doppler images. We identify two examples of this design capability that does not complicate further the at-sea system since the pulse design is carried out at a laboratory or sonar design house prior to deployment and the capability is added to the repertoire of pulses available to the operator. Some of the advantages of these pulses are that all N beams can be transmitted simultaneously resulting in high scan rate- high resolution imaging along with the other advantages of frequency hopped signals such as their better noise rejection and low sensitivity to spreading effects.

With these factors in mind as some of the influences we have observed in the signal designs reviewed, we now commence the list of signals that have been identified to date. No attempt has been made to rank the signals or to order the signals in any particular list, other than to put the continuous active signals found, together and to roughly class the pulse types as DS, DI or composite.

3. CONTINUOUS ACTIVE SIGNALS

3.1. Alion Science and Technology Corp

Alion Science and Technology Corporation has a US patent #7,106,656 for an FM based continuous active signal[10] and a processing arrangement which has been trialed at sea on several occasions. The British 2087 was one sonar system that was fitted with the Alion capability. Their claim is that the continuously emitted signal offers more time for signal processing, hence more gain, than the shorter duration pulse type signals. They do require Doppler shifted replicas and the received signal is heterodyned with the transmit waveform. The heterodyned output gives a start frequency depending on time delay (range) and the Doppler shift of the start frequency. Their analysis shows good gain against a noise only background and some gain in a reverberation background as compared to a single 1 sec LFM signal. Without spending a lot of time, I think this is a weak CAS system when compared with a pulse sonar using Costas pulses and PTFM signals being two pulse types which should perform as well or better than the Alion CAS, based on the information available.

They have a valid case for latency and convergence of motion estimates but at long range one needs to ask if these attributes are important. They also claim lower power requirements, i.e., lower source level than the pulse system but this puts into question their claim for detection gain in the reverberation background when operating against modern pulse designs.

3.2. M Sequence

The second signal type that has been applied to continuous active sonar is that based on M-sequences[9,39]. These signals have been around in sonar for at least 40 years with research led by Birdsall [41, 42] and Metzger[11] accounting for much of their recent successes. The problem has been processing load and Doppler induced losses. By the year 2000, these problems had been pretty much overcome and "CAMS" [40], Continuous Active M-Sequence Sonar was proposed in 2004. Others working with similar signal types, the BPSK[12], were not applying all the algorithms in the receiver as required for optimum performance and have not been quite as successful as the CAMS. The M sequence at about 10sec in length and 2047 sequence length, offers simultaneous 7.5m range resolution and 0.1Hz Doppler resolution. The transmitter tone is simple in that values of +1 and –1 are used to modulate the phase of a simple 4 cycle CW signal, as one example. The real work with this signal is in the receiver signal processing which requires a specific sampling rate, the formulation of complete ortho-normal data sets and the use of the Hadamard transform for lowering the work load. The next step is the Doppler waveform processing, trying to compensate for Doppler stretching and shrinking of the signal. A Doppler search is required and zero Doppler clutter removal[13] is applied for improved noise limited operation.

At LFA frequencies around 1kHz, Doppler resolution of the order of 0.1kt and range resolution of the order of 1m simultaneously has been demonstrated with sea-trials data. The reduced source levels required with this signal make it attractive in mammal mitigation circumstances and in power constrained operations.

This signal also has potential application in a pulse type sonar and will be restated in this list also.

4. DOPPLER SENSITIVE SIGNALS

Here we shall be concerned with pulse type systems whose signals are seen as having good Doppler resolution properties and medium to low range resolution.

4.1 Long CW

The long CW signal is obvious and gives good Doppler resolution up to the limits of the medium and is effective against targets moving with radial velocity that is sufficient to separate their echo from that of the scatters that are stationary. The range resolution of such a signal is very low.

4.2. Costas Frequency Hopped Signals

Costas frequency hopped wavetrains[2, 14] – Costas was the first to recognize that if the parameters of a pulsetrain are properly chosen, the range and Doppler responses will be unambiguous. He also demonstrated that if the firing order was derived from a set of permutation matrices then the range Doppler sidelobes could be well controlled. The design of Costas signals, with their at most one to two hit sidelobe level, are well understood and have achieved wide acceptance in most active sonar systems. These signals provide medium to good resolution in both range and Doppler and in practice Tukey shading of the main transmission or the individual sub-pulses

within the wavetrain has been applied to further enhance the performance of this signal type.

4.3. Costas Multi-User

(i) Welch

Costas array extension for multi-user applications[15] – In a spread spectrum multi-user system all signals occupy the same available bandwidth so that each receiver is receiving the signals from all other users. In multi-statics this can be turned into a system additional capability since each receiver can then process the signals from a variety of sources. However, this can only work if the cross-talk between pairs of signals is low, since if not, it can also cause errors in the system. Frequency-hopped, coded signals have good auto-ambiguity properties and it has been determined that by using different matrices for the code generation the cross-ambiguity function can also be controlled. In fact two theorems have been provided where, if x_1 and x_2 are reciprocal primitive roots of an odd prime p, then the resulting Welch-Costas arrays have at most two hits in their cross-hit array. However in some cases there can certainly be more than two users, so it is important to examine the number of hits in the cross-hit array for each prime number upon which the Welch-Costas arrays are derived. Careful selection of the Costas arrays can yield good cross-ambiguity properties and they are suitable for use in multi-user sonar systems and/or combined mono-static, bi-static scenarios.

(ii) Cubic Congruent

Multi-user Capable Frequency Hopped Signals[16] – Costas arrays in general do not have very good cross ambiguity properties even though as shown above there are some sequences that do have a low number of hits. However, a new family of frequency hop codes, called cubic congruence codes, have been identified which limit the number of cross-hits to 3 or less for a number of sequences. This code construction is based on the number theoretic properties of congruencies. Cubic congruence codes have at most two hits in their auto-ambiguity functions, while at the same time have uniformly good cross-ambiguity properties that tend to lower the sidelobe level in this function. Both the Welch-Costas and cubic congruence code sets can be applicable in multi-user systems. With only one user the Welch-Costas can offer a full set of codes for every prime while the cubic congruence codes are full for approximately half the primes. This should not be too much of an inconvenience since most signals are predetermined prior to at-sea trials and the number of signals available when p=17 can be adequate for most all scenarios.

4.4. Comb Spectrum Signals

The next few signals are all part of a grouping called comb signals because of the spectral properties they exhibit. These signals, in no special order, are:

a) The sinusoidlly modulated or SFM signal[3]
b) The Cox Geometric Comb Waveforms[6]

c) The Newhall comb-trains[17]
d) The triplet pair comb[7]
e) The Hermite Function Space comb[4]

The later two signals are the result of work by Naval Research Scientists in San Diego and the later one has a patent even though it is based on a radar signal design concept. They are not in use at sea as near as can be determined and for this reason we will not discuss these last two listed any further.

The other three comb signals have been trialed at sea and have produced some favorable results. These signals all have large Doppler ambiguities and careful design must be taken to ensure that these do not appear in operationally useful target velocities. For the SFM this spacing is controlled by the modulating frequency selection. For the Newhall train the approach is a convolution of a sub-pulse (a single cycle) with a train of impulse functions and the Fourier transform can be expressed as the product of a series of impulses and the spectrum of the sub-pulse. Newhall then recognized that if the energy was to be spread as evenly as possible across the band, the sub-pulse must have a flat uniform spectrum; i.e., an LFM chirp. The Cox comb is an attempt to address the Doppler sidelobe spreading observed with the SFM and Newhall trains. Since the Doppler shifts will vary across the bandwidth, it was observed that the spectral peaks should not be uniformly spaced but should be geometrically spaced. The overlap between adjacent peaks would then occur at the same Doppler scaling across the whole pulse bandwidth. The only way to construct such a pulse is by adding together individual tones derived according to the Cox geometric comb equation. The significant disadvantage of Cox combs, is that their amplitude envelopes are no longer smooth as per the SFM and Newhall but have large peak values compared to the mean. In most peak power limited systems, i.e., sonar linear power amplifiers, this high peak to RMS power ratio results in a loss of average power and hence a degradation in ambient noise detection capability.

To summarize, the comb signals are good Doppler sensitive signals with low range resolution. The SFM and Newhall are the most practical for real sonar systems use and while the Newhall is a bit better performer, the simplicity of the SFM would tend to favor this signal over the others for sonar trials of this signal type.

4.5. PTFM

One further Comb type signal that has been studied by the Dutch lab, TNO, is the PTFM, a pulse train of short linear FM signals[18]. Within the scope of this paper it is difficult to ascertain the difference between this signal and the Newhall train. However TNO did a nice LFA experiment where a target was stopped, slowly moving and moving at speed and the PTFM signal showed very good performance against the slowly moving target as compared to the CW and the HFM signals. No record was found of the performance of this signal compared to Costas signals but one reference[19] did give a favorable comparison to the BPSK signal. This pulse or the Newhall equivalent may be worthy of inclusion in any LFA sonar where the conditions of search versus target speed, are well defined. However, the composite signals could negate this statement following further at-sea trials with these signals.

5. DOPPLER INSENSITIVE WAVEFORMS

5.1. LFM and HFM or LPM

The linear frequency modulated (LFM) and hyperbolic frequency modulated (HFM) are the two key signals in this categorization with the HFM being the main working waveform in most active sonars. When reverberation background is the dominant noise and accurate ranging on a suspected target is required, the signal of choice is the HFM. It is a necessary signal with various pulse lengths and pulse bandwidths available to the operator to assist in detection and tracking in a wide range of operating conditions. These signals can be employed both with and without Tukey or Hamming shading, again environment and target speed dependent.

5.2. Rooftop and Vee FMs

Rooftop or Vee HFM or LFM – here for the rooftop an upsweep of the signal is followed by a downsweep and for the Vee, the signal sweep is down followed by an up sweep. These signals give good range resolution and the small advantage seen for this form of signal is that within one transmission, two slightly different looks at the possible target are available. There is also a patent(20) on Doppler estimation from these signals by delaying the matched filter output from the first half so that it aligns with that of the second half. Then adding the two outputs together the effect of the Doppler shift will sum and the position of the peak will be indicative of the target Doppler.

5.3. PRN

Pseudo random noise (PRN) signals(21) – Some would argue that these signals should be good at both Doppler and range resolution but other writers have claimed that their Doppler resolution is low and so this class of signal has been put in the Doppler insensitive category. It is not a serious contender in any new sonar because the PRN sequence is not unimodular and the energy has to be normalized so that the power amplifier can properly transmit the signal without distorting. The PRN sequences are Gaussian random processes and as such are not constrained to be unimodular.

5.4. Golay Pairs and Exponential Codes

There are two further signals which have been identified in this group, the Golay complementary pairs(22, 23) and the waveform designed using exponential residue codes(24). Golay complementary pairs have some interesting cross-correlation properties and are used in orthogonal frequency division multiplexing schemes which have been designed to fight multipath induced frequency selective fading. The signal design based on exponential residue codes is another pulse type from the Naval Undersea Center, San Diego and is a set of codes whose periodic autocorrelation functions have a constant sidelobe height relative to the height of the main lobe. Work on Golay pairs is progressing in the communications area but we have not found any sonar references. Waveforms, that are based on exponential residue codes, do not appear to have progressed beyond the original paper. This does not mean that these signals have not been tested at sea, it is just that within the constraints of this investigation we have not been able to uncover any papers with trial results.

6. COMPOSITE SIGNALS

The area where most of the recent waveform research has been centered has been in the area of designing signals to effectively mitigate the problems encountered in shallow water by low frequency multi-static sonars. In general the goal has been to provide good range resolution for a Doppler sensitive signal and that generally means lower sidelobe levels after range compression. This in turn means lower interferences among scatters located at different range bins. The approaches have been quite variable and in this section of the report we will list those, which we have identified.

6.1. Combined DS and DI (additive)

Combined DS and DI waveform(5) – Under a US Navy Transition Assistance program, waveforms for energy constrained multi-static sonar, is investigating one signal for active buoys which seems to be progressing toward operational trials and it is the composite signal made by the coherent sum of a DS and a DI waveform. The two components offer complimentary coverage in the Doppler-time domain. The detection of the low Doppler echos requires a modified hyperbolic frequency modulated (HFM) filter for suppressing the reverberation from the DS waveform. The modified HFM has the spectrum of the regular HFM but with notches at the frequencies present in the DS waveform. This signal was planned for sonobuoy trials with an updated receiver software package to handle the composite signals last fall. No written report on whether this occurred and/or how successful the trials were, has been located

6.2. M-sequence Pulse

M-sequence pulses(9, 25) – This signal and its associated receiver processing has been briefly outlined in the continuous active signals and is listed here again since there are some pulse systems which employ this signal type. As pointed out previously, these signals have a large impact on the receiver signal processing but this also appears to be the case for some other of the composite signals identified, not just the M-sequence pulses.

6.3. BPSK with Large Bandwidth Duration

Large bandwidth-duration binary phase shift keying signals – Binary phase shift keyed signals have received attention in the European sonar community, both Dutch(19) and French(12). They both appear to use the signals and their associated multi-Doppler matched filtering for tracking and classification purposes but not for detection. In one French paper(12) it is stated that if the SNR is assumed large enough then this should permit the target highlights to be extracted, while if not, the problem is viewed as a detection problem and the choice of optimal signal will be different than the large WT BPSK signals. The Dutch paper analyzed some challenging at-sea data and observed that sonar motion and propagation may be the cause of some performance loss observed. They did find that considerable signal processing was required for the BPSK signals but that the signal did enable good classification possibilities for separating clutter-like reverberation from a

moving submarine. Perhaps the key statement was their view that the BPSK can be used as a classification tool as long as detection is being performed with another pulse (FM).

6.4. Combined DS and DI via Phase Modulation

Arbitrary Combined Sonar Signals[25] – this section of the report has emphasized the need for multiple sonar signals to be transmitted simultaneously in order to capture the key capabilities of each signal. (See above) However in peak power limited systems, adding signals, i.e., amplitude modulating, has been shown to cause severe losses. The way around this problem has been investigated by several researchers and they have found that by linearly combining the desired sonar signals as the modulating phase component of a carrier signal, allows multiple sonar signals to be transmitted simultaneously and upon reception and demodulation, separated and processed in parallel. Some signals listed further on in this report also use a similar technique to allow multiple beams or look directions to be scanned simultaneously in systems with multiple transmit devices. This technique can also be applied to narrowband and broadband signals as well as DS and DI signals. This process of generating multiple signals simultaneously is known as sub-band modulation. Based on 6.3 above the use of this technique could allow the simultaneous transmission of the HFM and BPSK signals to achieve the detection and false alarm rate reduction which was desired.

6.5. Costas FM Train

Costas FM train[19] – In this waveform the sub-pulses are selected in time and frequency space according to the Costas FH codes but instead of each sub-pulse being CW based, these are replaced by LFM sub-pulses. This is not too dissimilar from the TNO PTFM signal except that lower sidelobe levels in the individual matched filters allows for improved detection of low speed targets in a highly reverberant background. Having improved range resolution and moderate Doppler resolution, this signal is another potential candidate for a combined capability signal.

6.6. Time Split Pulse

Time split pulse[26] – A pulse design for bi-static sonar operations which minimizes the effects of direct blast interference and reduces the potential for mutual target interference. Here the transmission is divided into a wavetrain of noncontiguous pulses with non-uniform spacings where the spacings are described by a code. In one paper, orthogonal optical codes are used to determine the spacing and minimize the interference. In another paper [38] the orthogonal codes are used to extend the aperture of the MIMO system for improved angular resolution.

These signals may be of interest but the lack of follow-on work and at-sea testing would seem to indicate that these designs are of marginal interest.

6.7. Constrained Component Sequence Design (CAN)

Constrained component sequence design[8, 27]. Given that some interference in the detection of weak signals can be caused by correlation function sidelobe levels of the transmitted waveform, a new class of transmitted waveforms, that are designed to be unimodular, have been developed for minimization of the autocorrelation integrated sidelobe level (ISL). The algorithm called CAN (cyclic algorithm new) uses a cyclic minimization of the ISL related metric to derive a sequence of the desired length and bandwidth. These signals compare very favorably with the PRN[21] designs and the RP[34] designs since lower sidelobe levels due to the optimization employed are particularly effective in the area of zero Doppler and very low Doppler signal detection. However the sidelobes of the CAN sequence in other parts of the ambiguity space are similar to those of the PRN and RP sequences. A second case where the CAN signal will do better on weak signals than the other two signal types exists only when two targets separated in range, occupy the same Doppler bin. These caveats apply when all the signals are processed using a matched filter (MF) receiver. The CAN sequence is also helped by improved adaptive receiver algorithms[28,29,30] which can be used in place of the matched filter. The use of these new sequence design algorithms provides the sonar designer and user with another tool for use in the detection of targets under specific sets of circumstances. While perhaps making sonar operation a bit more challenging initially, after careful evaluation and the combining of the transmitted pulse design with the appropriate receiver algorithm, the shallow water reverberation effects on the detection of both high and low Doppler targets can be significantly reduced through the use of these new pulse designs. The enhanced resolving power of these signals may also provide clues for use in automatic target recognition.

6.8. Signal Designs for Beampattern Synthesis

Signal design for transmit beampattern synthesis[31,32] – As another example of the use of constrained sequence design, there is the opportunity in a MIMO system, where different elements of the transmitter can freely transmit different waveforms, to constrain the transmit beampattern. Here the goal is to match a transmit energy distribution in both space and frequency. Designs are available to accommodate both wide bandwidth and narrow bandwidth signals. While not applicable to a VP-2 type transmitter, the concepts and algorithms are applicable to the in-line projector arrays (i.e., Barrel-stave) and could help make such a system more effective. Work in this area has shown that for wide beamwidths, it may be difficult to manage the sidelobe levels in non-look directions while maintaining unimodular pulses but if the peak to average level can be allowed to vary by a factor of two, then the sidelobes can be lowered significantly.

7. RECEIVER MODIFICATIONS

As has been shown with many of the sequence derived signals, M-sequence, BPSK, etc., mismatching the filter to account for medium and target effects can often lead to improved detection possibilities[33,11]. One of the first to be employed was matching the

replicas to a specific Doppler so that a bank of matched filters was employed to cover the expected Doppler range.

In the cases where the combination of the newer pulse sequence designs, such as CAN, and the matched filter receiver do not provide as much sidelobe attenuation as desired, then the matched filter can be replaced by more advanced receiver designs. One such algorithm is the instrumental variables (IV) receiver[35,36,37] which is pre-computed offline and has been shown to significantly minimize the clutter effects in the received signal for negligible Doppler cases. When Doppler effects are considered, IV filters are not quite as effective and additional algorithms are often required. However this algorithm is very efficient being of similar complexity as the matched filter and does not have amplitude constraints. The filter can be designed to minimize the integrated sidelobe level (ISL) for the signal that was transmitted. Doppler can be included in the design constraints over a limited Doppler range. To date no papers were located which compared the matched filter and IV filter in a real data limited Doppler sonar scenario.

In some of the newer pulse designs aimed at the low Doppler target in shallow water regions, the Doppler range of interest for these signals may be of the order of ±4kts and with a 0.2kt resolution, about 40 Doppler bins need to be covered by the adaptive receivers. Many such receivers have been looked at and with various amounts of complexity have shown some modeled improvements over the standard matched filter. One algorithm, the iterative adaptive approach (IAA)[28], can produce good results but the computational effort, at least the Matlab implementation, is roughly 1800 times that of the matched filter. Another algorithm has been proposed which has been found to be nearly as effective as the IAA but many times faster. This algorithm is known as a sparse signal recovery algorithm and is referred to as the sparse learning via iterative minimization (SLIM)[8] method. Recent papers have reviewed the computational issues with SLIM and introduced a fast implementation of the algorithm. The new approach exploits the structure in the steering matrix and makes the matrix-vector multiplication computationally efficient using the FFT. A conjugate-gradient (CG) approach has been used to transform the matrix inversion into a series of matrix-vector multiplies. The result is an algorithm that appears to require 20 to 40 times the computation of the matched filter but given the potential gains may be worth further investigation.

8. SIGNAL SELECTION

There are several good candidate designs all of which are aimed at providing multi-static sonar operations with specific advantages in certain areas.

Should mammal mitigation be a primary objective, then continuous active using the M-sequence based signals will be the best choice from what has been reported.

To achieve as good and/or better performance in a pulse based sonar, a repertoire of signals will be required to provide the operator with near optimum performance in a variety of scenarios. The first signal is the HFM that would probably require two or three

instantiations as to the bandwidth and pulse length. The HFM would be a good search signal but with low Doppler resolution may not be the best tracking signal.

The second signal for the pulse system would be a CW based Costas array. Here several designs will need to be available in terms of bandwidth, sub-pulse length, total pulse length, single user/multi-user types and sequence length. This signal type is also a very capable search and track type signal but will suffer against very low Doppler targets in shallow water.

In order to reduce the reverberation effects, false alarm rates and trackers going off target, it is worth having a modified Costas where the bandwidth of each sub-pulse and hence the total pulse bandwidth, is increased by virtue of using an LFM sub-pulse signal in place of the CW. This gives an added processing advantage against the lower Doppler contacts.

The final pulse that should be considered is the cyclic algorithm new (CAN) sequence design algorithm, with the constraint of minimizing the integrated sidelobe level (ISL). This signal has a high merit factor especially against the very low Doppler targets. Once the design is completed for the desired length sequence, i.e., pulse length and bandwidth, then these signals can be included in the sonar's pulse library for use in the appropriate search and track situations.

9. RECEIVER SELECTION

All four pulse type signals described above can use a matched filter as the classic receiver type. The Costas signals employ both coherent and incoherent steps in the processing and a variable controlled delay is required to align the sub-pulses prior to incoherent integration. In some cases even the careful selection of the transmit waveform parameters, when coupled with a matched filter at the receiver, sufficient sidelobe reduction may not be provided to the level desired. In this case a newer type range compression algorithm may have merit and as the previous discussion concluded, the sparse learning via iterative minimization (SLIM) method is worthy of further investigation. Also a series of mis-matched filters which take into account the different Doppler shifts for each of the sub-pulses should be considered. This adjusted bank approach to the Costas signal processing may reduce some of the undesired sidelobe effects.

A computational comparison was run using Matlab R2009 and a Xeon 2.339GHz CPU with 16GB of RAM. The matched filtering, IAA and SLIM algorithms were run on a range section from 1.3km to 1.7km and with Doppler coverage of 40 cells covering ±4kts with 0.2kt resolution. The signal center frequency for the example was at 900Hz, with a 200Hz bandwidth and an 8000Hz sampling rate. There were two targets, one 14dB larger than the second and moving away at 1kt and the target of interest was moving at 2kts radial velocity approaching. The matched filtering took 0.5sec of computation time, the SLIM algorithm took 25sec and the IAA algorithm required 1800sec.

Generally the matched filter had a difficult time seeing the second target, the IAA got this same target and SLIM got it most of the time. In fact using ten independent simulations the SLIM algorithm made 6 detections but the second target levels were low compared to the interference target, while the IAA algorithm was successful every time and reported the second target at the appropriate level.

In the pulse type system, a receiver employing the matched filter as the primary processing algorithm is the obvious choice for many water conditions and scenarios. The Office of Naval Research (ONR) has continued to fund the adaptive algorithm work and a fast SLIM algorithm is now available. It would appear that this algorithm is worth some further investment to assess its performance with sea data from various shallow water environments. A second possibility is the application of this algorithm in the DIFAR processing where fewer beams are involved but the potential gain from the algorithm could potentially compensate for the lower directivity index.

If for stealth reasons or environmental concerns, the continuous active signaling is selected, then the receiver can also have more than one possible implementation. However assuming a continuous M-sequence, the signals +1 and –1 could be used to modulate the phase of a 4 cycle CW signal. With clocks aligned, this signal is said to have a matched period phase shift. The signal processing steps are briefly listed for this signal which is classed as a long continuous M-sequence transmission; first the data would be sampled at the beamformer output to form a complete ortho-normal (CON) data set of the received waveform. Next a pulse compression by Hadamard transform (HT) for zero Doppler pulse response; zeroing the direct blast, multi-path arrivals and reverberation peaks (HCCO); then IHT to a waveform. Perform a linear temporal Doppler search, really linear interpolation in the time domain as per (Metzger). Next do an HT for every Doppler bin waveform to compute a Doppler/arrival time plane. The final step is then detection. While this may appear to be a lot of steps the Hadamard transform is quite efficient to compute and the details of the linear temporal Doppler search are well described.

This algorithm has been tested and used in at-sea trials with some good results. The signal used was a 2047 length sequence and gave simultaneous Doppler resolution of the order of 0.1kt and range resolution of 1m. For best results it appears that the zero Doppler clutter removal along with the Doppler interpolation are key steps in allowing the target signals to essentially be detected in a noise limited environment. The results are gains of the order of 30dB over a simple CW and 10dB over a 1sec FM. These results do require the use of Coordinate zeroing (CZ) which is another well described and very simple procedure, setting the appropriate values to zero, which as well as removing the zero Doppler terms, takes out their leakage (clutter) terms with them. In the continuous system averaging over several tens of seconds was shown to reduce the data rate without loss of detection capability but no mention was found of the sonar speed.

One further consideration would be to examine the IV algorithm for limited Doppler coverage, as yet another example of a computationally efficient algorithm for the control of sidelobe effects. Running this algorithm in parallel with the matched filter could

provide clarification on which peaks are potential targets and which may just be clutter sidelobes.

10. SUMMARY

Much work has been done in the application of coded signals to the detection of low Doppler targets in the shallow water environment. A recommendation has been made in the pulse type sonar for including at least four signal types in LFA sonar systems:

a) The HFM
b) Costas Frequency Hopped Signals
c) Costas based signal with LFM sub-pulses
d) The cyclic algorithm, new or CAN based signals.

The aim of the latter three signal types has been to provide good Doppler and range resolution simultaneously.

In the event that continuous active sonar using lower source levels is the preferred route, then an M-sequence based signal design is recommended as the preferred type.

To achieve the best performance possible from these signals, the use of mis-matched, matched filters and/or the use of adaptive algorithms as part of the sonar receiver, has been observed in the literature to show further clutter attenuation.

While not automatically recommended for inclusion initially, the newer phase modulation algorithms would be worthy of further investigation. One example would be the design of signals with more than one constraint, such as bandwidth and azimuthal direction. In the MIMO type system the ability to control the signals detection properties as well as the transmission beamwidth, is seen as a desirable feature. Several design methods for achieving this were identified, but further work is required to determine the optimum signal design procedure. As well as the algorithm selection, the transmitter hardware capabilities will need to be taken into account.

11. RECOMMENDATIONS FOR FOLLOW-ON WORK

This report has outlined several sonar signal designs for possible inclusion in the DRDC (A) LFA sonar trials. In addition several receiver algorithms were outlined which may be particularly helpful in the shallow water, high clutter environment. Assuming that the initial sonar trials will be with a pulse system and an omni-directional transmitter (VP-2 type) two pulses should be further investigated; (a) the PTFM based on Costas spacing of LFM signals, (b) the cyclic algorithm new (CAN) sequence constrained for integrated sidelobe level (ISL) minimization.

The PTFM signal should not require a large amount of design effort but the matched filter processing should be simulated for several Doppler shifts and SNRs. The frequency spreading of the clutter returns would be challenging to simulate but assuming the signal processing is simulated properly then sea-trials data could be easily imported for non-real-time processing and a comparison of the returns with those of the CW based Costas signals.

The CAN algorithm is a total design of a new signal waveform and the algorithms will require some initial set-up time before signals of the proper bandwidth and duration can be designed. Once the design has been achieved for a few instantiations of the signal, then matched filter processing should be simulated for various Doppler shifts and SNRs as per the above. Again sea-trials data could be collected and imported to the simulation environment for comparison, this time with a standard HFM pulse.

While the receiver algorithms were not part of this investigation several new algorithms were identified as offering detection performance benefits. Follow-on work could investigate further the IV and the SLIM algorithms with the goal of producing a simulation environment where sea-trials data could be easily imported and re-analysed using the new algorithms. These results could then be compared against the standard match filter receiver results with respect to signal detection, contact range and Doppler accuracy.

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LIST OF ACRONYMS

B	*Signal Bandwidth*
BPSK	*Binary Phase Shift Keying*
CAN	*Cyclical Algorithm New*
CAMS	*Continuous Active M-sequence Sonar*
CG	*Conjugate Gradient*
CW	*Continuous Wave*
CZ	*Co-ordinate Zeroing*
DIFAR	*Directional Frequency Analysis and Recording*
DI	*Doppler Insensitive*
DS	*Doppler Sensitivity*
FH	*Frequency Hopped*
FM	*Frequency Modulated*
HFM	*Hyperbolic Frequency Modulation*
HCCO	*Zero Direct Blast, Multi-path Arrivals and Reverberation Peaks After HT for Zero Doppler Pulse Response*
HT	*Hadamard Transform*
IAA	*Iterative Adpative Approach*
IHT	*Inverse Hadamard Transform*
ISL	*Integrated Sidelobe Level*
IV	*Instrumental Variables*
LFA	*Low Frequency Active*
LFM	*Linear Frequency Modulation*
LPM	*Linear Period Modulation*
MISO	*Multiple Input Sin\le Output*
MIMO	*Multiple Input Multiple Output*
ONR	*Office of Naval Research (US)*
PTFM	*Pulse Train of FM Signals*
PRN	*Pseudo Random Noise*
RP	*Random Phase*
SLIM	*Sparse Learning Via Iterative Minimization*
SNR	*Signal to Noise Ratio*
T	*Signal Duration*
TB	*Time Bandwidth Product*
VP-2	*Dual Free Flooded Ring Projector*
WT	*Bandwidth Time*